Earth and Planetary Science Letters 393 (2014) 254–265

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Evidence for multiple magma ocean outgassing and atmospheric loss episodes from mantle noble gases

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A R T I C L E   I N F O

Article history:
Received 22 July 2013
Received in revised form 14 February 2014
Accepted 26 February 2014
Available online 25 March 2014
Editor: T. Elliott

Keywords:
accretion
magma ocean
giant impact
noble gases
terrestrial volatiles

A B S T R A C T

The energy associated with giant impacts is large enough to generate global magma oceans during Earth's accretion. However, geochemical evidence requiring a terrestrial magma ocean is scarce. Here we present evidence for at least two separate magma ocean outgassing episodes on Earth based on the ratio of primordial ^{3}He to ^{22}Ne in the present-day mantle. We demonstrate that the depleted mantle ^{3}He/^{22}Ne ratio is at least 10 while a more primitive mantle reservoir has a ^{3}He/^{22}Ne ratio of 2.3 to 3. The ^{3}He/^{22}Ne ratios of the mantle reservoirs are higher than possible sources of terrestrial volatiles, including the solar nebula ratio of 1.5. Therefore, a planetary process must have raised the mantle's ^{3}He/^{22}Ne ratio.

We show that long-term plate tectonic cycling is incapable of raising the mantle ^{3}He/^{22}Ne ratio and may even lower it. However, ingassing of a gravitationally accreted nebular atmosphere into a magma ocean on the proto-Earth explains the ^{3}He/^{22}Ne and ^{20}Ne/^{22}Ne ratios of the primitive mantle reservoir. Increasing the mantle ^{3}He/^{22}Ne ratio to a value of 10 in the depleted mantle requires at least two episodes of atmospheric blow-off and magma ocean outgassing associated with giant impacts during subsequent terrestrial accretion. The preservation of a low ^{3}He/^{22}Ne ratio in a primitive reservoir sampled by plumes suggests that the later giant impacts, including the Moon-forming giant impact, did not generate a whole mantle magma ocean.

Atmospheric loss episodes associated with giant impacts provide an explanation for Earth's subchondritic C/H, N/H, and Cl/F elemental ratios while preserving chondritic isotopic ratios. If so, a significant proportion of terrestrial water and potentially other major volatiles were accreted prior to the last giant impact, otherwise the fractionated elemental ratios would have been overprinted by the late veneer.

1. Introduction

Global magma oceans are thought to be a natural result of the highly energetic giant impact phase of planetary accretion (Abe and Matsui, 1985; Benz and Cameron, 1990; Canup, 2008; Elkins-Tanton, 2012; Sasaki and Nakazawa, 1986; Stevenson, 1987; Tonks and Melosh, 1993). The best evidence for a terrestrial magma ocean is the relative concentrations of siderophile elements in the mantle, which suggest core formation occurred when at least part of the Earth's mantle was molten (Li and Agee, 1996; Righter et al., 1997; Rubie et al., 2007). However, elements that trace silicate differentiation do not show strong signatures for a magma ocean. For example, Kato et al. (1988) and Ringwood (1990) argued that refractory lithophile trace elements should have been highly fractionated by magma ocean crystallization and that fractionation is not observed in Hadean zircons, which preserve chondritic ratios. On the other hand, magma ocean crystallization models have been used to explain incongruent Sm–Nd and Lu–Hf isotope systematics in Archean rocks (Caro et al., 2005; Rizo et al., 2011) as well a slightly superchondritic mantle Ca/Al ratio (Walter et al., 2004). Geochemical evidence for a magma ocean may be difficult to find in the present-day mantle, as crustal recycling and mantle mixing throughout Earth's history may have erased the chemical fractionations of the lithophile elements produced by magma ocean crystallization.

The noble gases may provide unique information on the occurrence of magma oceans, as magma ocean ingassing or outgassing will create large fractionations in noble gas elemental ratios due to their different solubilities in magma. The present-day budgets of nonradiogenic Ar, Kr, and Xe in the mantle are dominated by recycled air (Holland and Ballentine, 2006; Kendrick et al., 2011; Mukhopadhyay, 2012; Pető et al., 2013; Sumino et al., 2010; Tucker et al., 2012), so possible magma ocean degassing signatures involving Ar, Kr, and Xe would have been overprinted by subduction. On the other hand, He and Ne are not recycled back into the mantle in significant quantities, and may preserve ancient

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http://dx.doi.org/10.1016/j.epsl.2014.02.050
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magma ocean signatures (Harper and Jacobsen, 1996; Honda and McDougall, 1998; Porcelli et al., 2001; Shaw et al., 2001; Yokochi and Marty, 2004).

Honda and McDougall (1998) observed that the mantle $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ratio, as determined from measurements of mid-ocean ridge basalts (MORBs) and ocean island basalts (OIBs), was twice the solar value, and suggested that this fractionation resulted from the higher solubility of He compared to Ne during magma ocean outgassing. Ingassing, i.e. dissolution of volatiles from an accreted nebular atmosphere into a magma ocean (Harper and Jacobsen, 1996; Mizuno et al., 1980), could also have the same effect on the mantle $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ratio. However, magma ocean equilibration (ingassing or outgassing) has been regarded as a speculative explanation of the high mantle $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ratios (e.g., Graham, 2002). Yokochi and Marty (2004) advocated magma ocean ingassing based on observations of $^{20}\mathrm{Ne}/^{22}\mathrm{Ne}$ ratios of >13.0 in the Kola plume, a Ne isotopic composition similar to the solar wind. The authors also noted that the high $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ratio ($\sim$7.9) observed in the Kola plume and in present-day MORBs requires additional fractionation beyond that capable through magma ocean ingassing. They speculated that the fractionation mechanism was fluid-melt partitioning during high pressure melt segregation and fluid phase formation in the deep mantle. However, it is unclear whether fluid phases would nucleate at the P–T conditions of the deep mantle.

Here we present evidence for ancient magma ocean degassing based on high $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ratios in the depleted mantle that are more extreme than the average MORB value. To establish the $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ratio of the depleted mantle, we characterize how $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ variations are linked to lithophile (Pb, Sr, Nd) and noble gas isotope ratios in very depleted to enriched MORBs using published data from the equatorial Atlantic (Agranier et al., 2005; Schilling et al., 1994; Tucker et al., 2012). We then show that magma ocean degassing is the most likely explanation for the large $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ fractionation observed in the present-day mantle. We demonstrate that extraction of He and Ne from the mantle through partial melting and plate subduction associated with plate tectonics either has a negligible effect or decreases the mantle $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ratio. We argue that the magnitude of the $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ fractionation requires atmospheric loss followed by solubility-controlled degassing of at least two separate magma oceans during the giant impact phase of Earth's accretion.

2. Determining MORB mantle source $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ratios

Direct measurements of $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ratios in mantle-derived basalts are not likely to represent the mantle value because the ratio can be changed by magmatic degassing during eruption and ubiquitous shallow-level air contamination. We therefore calculate the mantle source $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ($^{3}\mathrm{He}/^{22}\mathrm{Ne}_m$) ratio from measured He and Ne isotope ratios in basalts, after Honda and McDougall (1998) and Porcelli and Ballentine (2002) (Method 1):

$$^{3}\mathrm{He}/^{22}\mathrm{Ne}_m = \frac{^{21}\mathrm{Ne}/^{22}\mathrm{Ne}_E - {}^{21}\mathrm{Ne}/^{22}\mathrm{Ne}_i}{^{4}\mathrm{He}/^{3}\mathrm{He}_{meas} - {}^{4}\mathrm{He}/^{3}\mathrm{He}_i} \times \left(^{4}\mathrm{He}/^{21}\mathrm{Ne}\right)^{*}_{production} \tag{1}$$

$^{21}\mathrm{Ne}/^{22}\mathrm{Ne}_E$ is the mantle source $^{21}\mathrm{Ne}/^{22}\mathrm{Ne}$ ratio corrected for shallow-level air contamination by extrapolation of measured $^{21}\mathrm{Ne}/^{22}\mathrm{Ne}$ ratios to the mantle $^{20}\mathrm{Ne}/^{22}\mathrm{Ne}$ ratio of 12.5 (Tucker et al., 2012). $^{21}\mathrm{Ne}/^{22}\mathrm{Ne}_i$, the initial $^{21}\mathrm{Ne}/^{22}\mathrm{Ne}$ ratio for the mantle, is 0.0313, corresponding to a $^{20}\mathrm{Ne}/^{22}\mathrm{Ne}$ ratio of 12.5. The primordial He isotope ratio $^{4}\mathrm{He}/^{3}\mathrm{He}_i$ is 6024 (120 R_A), as observed in the Jovian atmosphere (Mahaffy et al., 1998), and $(^{4}\mathrm{He}/^{21}\mathrm{Ne})^{*}_{production}$ is the production ratio of radiogenic $^{4}\mathrm{He}$ to nucleogenic $^{21}\mathrm{Ne}$ in the mantle.

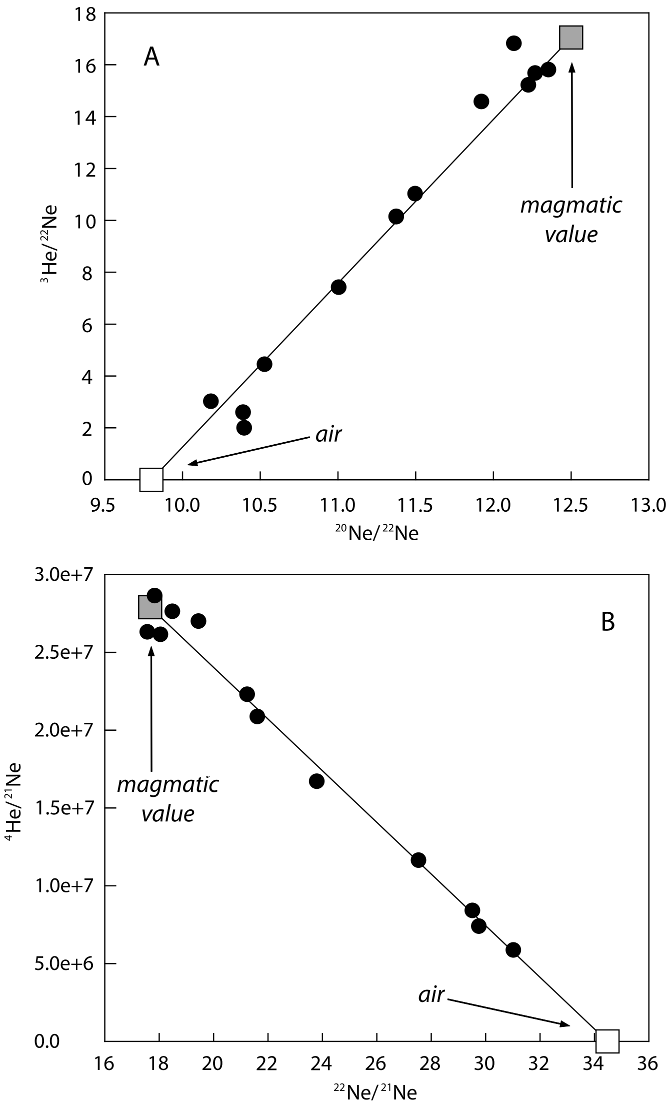

Fig. 1. Example of correlation diagrams to determine the MORB source $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ($^{3}\mathrm{He}/^{22}\mathrm{Ne}_m$) ratios. Each point represents a single crushing step of the equatorial Atlantic MORB sample RC2806 42D-7 (data presented in Tucker et al., 2012). Step-crushing releases gas trapped in vesicles that reflects magmatic gas variably contaminated with a post-eruptive atmospheric contaminant. Extrapolation of the (a) $^{3}\mathrm{He}/^{22}\mathrm{Ne}$–$^{20}\mathrm{Ne}/^{22}\mathrm{Ne}$ and (b) $^{4}\mathrm{He}/^{21}\mathrm{Ne}$–$^{22}\mathrm{Ne}/^{21}\mathrm{Ne}$ correlation trends to the uncontaminated mantle values of $^{20}\mathrm{Ne}/^{22}\mathrm{Ne} = 12.5$ and $^{22}\mathrm{Ne}/^{21}\mathrm{Ne}$ (determined by correlation of $^{20}\mathrm{Ne}/^{22}\mathrm{Ne}$ with $^{21}\mathrm{Ne}/^{22}\mathrm{Ne}$; Tucker et al., 2012) corrects for post-eruptive air contamination and establishes the magmatic $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ and $^{4}\mathrm{He}/^{21}\mathrm{Ne}$ ratios. This magmatic $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ ratio is corrected for potential magmatic degassing though the degree to which the magmatic $(^{4}\mathrm{He}/^{21}\mathrm{Ne})^{*}$ ratio is fractionated from the mantle $(^{4}\mathrm{He}/^{21}\mathrm{Ne})^{*}$ production ratio (see supplementary material).

We additionally calculate the $^{3}\mathrm{He}/^{22}\mathrm{Ne}_m$ ratio (Method 2) by first correcting the sample's measured $^{3}\mathrm{He}/^{22}\mathrm{Ne}$ and $^{4}\mathrm{He}/^{21}\mathrm{Ne}$ ratios for air contamination ($^{3}\mathrm{He}/^{22}\mathrm{Ne}_E$ and $^{4}\mathrm{He}/^{21}\mathrm{Ne}_E$; Fig. 1) and computing $(^{4}\mathrm{He}/^{21}\mathrm{Ne})^{*}$ (where '*' refers to the mantle-derived radiogenic/nucleogenic species) from $^{4}\mathrm{He}/^{21}\mathrm{Ne}_E$. $^{3}\mathrm{He}/^{22}\mathrm{Ne}_E$ is corrected for magmatic degassing by the degree to which the sample's $(^{4}\mathrm{He}/^{21}\mathrm{Ne})^{*}$ ratio is fractionated from the expected production ratio (e.g., Graham, 2002; see supplementary material). The two methods give comparable results for our MORB samples (Table 1).

In our calculations, we assume the MORB mantle $^{20}\mathrm{Ne}/^{22}\mathrm{Ne}$ ratio is 12.5 (Ballentine et al., 2005; Holland and Ballentine, 2006; Raquin et al., 2008; Trieloff et al., 2000). If we instead assume a MORB mantle $^{20}\mathrm{Ne}/^{22}\mathrm{Ne}$ ratio of 13.8, corresponding to the solar wind value (Grimberg et al., 2006), calculated $^{3}\mathrm{He}/^{22}\mathrm{Ne}_m$ ratios increase by $\sim$50%, strengthening our conclusions. Additionally,